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Transient behavior in complex distribution network: a case study

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Abstract

Water distribution systems typically contain large numbers of pipes joining sources of supply to consumers; in addition they include a number of ancillary devices such as pumping stations, valves, storage reservoirs and surge suppression devices. These ancillaries and potential flow control points create systems with complex, varied dynamic conditions. Presented here are the results of a field monitoring case study that evidences propagation of transients within complex distribution system. The outcomes test the common assumption that damping and dissipation of transient occurs due to system complexity while travelling through a network. Ultimately such work improves understanding of dynamic pressure behaviors in complex networks which may help assess vulnerability to transients.

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Keywords: transient, water distribution system, pipe network, field tests, wave propagation.

1. Introduction

Water Distribution Systems (WDS) are generally considered as being fairly steady state systems, with smoothly varying flows and pressures changing over minutes and hours. System dynamics are often only considered close to large control features, such as pump. The steady state assumption is reinforced by the current practice of collecting hydraulic data at 15 minute intervals. However, transients exhibiting rapidly cycling high and low pressures lasting just a small number of seconds can, and do occur, and may significantly exceed normal steady state pressures. There are a number of studies that consider the mechanisms of transient propagation and the potential causes (Kirmeyer & Martel 2001). Pump switching (on and off) is the most commonly recognized potential source of transient events, with results evident in pressure traces when recorded at sufficiently high rates (McInnis & Karney

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1995; Kirmeyer & Martel 2001; Soares et al. 2013). However, there is still limited knowledge about transient behaviour in complex water distribution networks, and a need to increase physical experimental data available to analyse. To address this, researchers at the University of Sheffield have undertaken a large scale systematic data collection project, where 40 high speed pressure loggers were installed at different locations, such as trunk, distribution and pumped mains. The data collected is being analysed and a case study is presented in this paper.

There is a common belief that transients will be naturally damped by network complexity, as noted by Karney (Karney & McInnis 1990).The assumption is that junctions, reflections, pipe infrastructure, and distance travelled will significantly damp and dissipate any transients. However, in their paper Karney and McInnis show simple modelled examples of cases where, due to the network configuration, the transient pressure in the system can be higher than at the source. Amplifications of the pressure waves have also previously been modelled by Ellis (Ellis 2008); in his model of a real system the downstream shut off of a pump caused a high pressure wave to be magnified into a distribution system. Ellis also attempted to correlate these high pressure events with pipe bursts.

2. Transient Propagation through a Complex Network

Pipelines in water distribution systems can generally be divided into two categories, trunk mains and distribution pipes. Trunk mains transport water from treatment works, but do not have any customer connections. A third category of pipes, supply mains, may be defined that connect the trunk mains to the distribution system, that is divided into District Metered Areas (DMAs). Supply mains usually include a flow meter to enable leakage and other management of DMA, and are hence often a viable location for other instrumentation. Trunk mains are typically dendritic in structure, while distribution pipes typically include multiple pathways and tend to comprise of looped networks to facilitate resilience.

Fast changes in the velocity of the fluid flowing in the pipe system; generated for example by the opening or closing of the valve, or starting or stopping of a pump, will be accompanied by rapid change in pressure, proportional to the change in velocity (if fast enough). The changes in pressure and velocity travel around the system as waves, which are known as transients.

Many studies have investigated the damping of pressure waves due to friction (Massey 2006; Wylie & Streeter 1978). The presence of friction in systems, as a first approximation related to the overall pipe velocity squared, has a tendency to decrease the magnitude of the pressure waves, until the system stabilizes at a new equilibrium. Strong damping and smoothing of pressure waves was observed and analyzed in detail from laboratory experiments. These effects have been associated with both friction and visco-elastic (Ramos et al. 2004; Riasi et al. 2013) and mechanical damping (Stephens et al. 2011).

Each time that a transient wave passes a change in pipe type, size, material, a valve or junction, a proportion of the wave is reflected with the rest propagating further into the system. The proportion of the wave that is transmitted or reflected at a junction is determined by the acoustic admittance of the incoming and outgoing pipes (Lighthill 1978). This often results in dissipation, but wave amplification can occur when the sum of the outgoing pipe admittances is lower than the incoming. This will arise when the outgoing pipes cross sections are lower or the wave's speeds are higher than the incoming pipes. Swaffield and Boldy (1993) derive simple relationships based on the area of flow and the acoustic wave speed in pipes to calculate these transmission and reflection coefficients. Some recent analysis of the interaction between transient pressure waves and sudden changes of cross-section area in a laboratory conditions were undertaken by Silvia Meniconi (Meniconi et al. 2011). These showed the wave rises that occurs due to the initial pressure change when passing through an abrupt contraction and decreases when travelling through a sudden expansion. In addition there was an overlapping of the pressure waves due to the changes in cross-sectional areas. Local head losses were also important in the case of in-line valves with regards to partial blockages.

The complexity of supply networks provide resilience but also complicate analysis of transient behaviour. The loops of a system, or reflections from junctions and dead ends, give the potential for superposition of two or more waves. Depending on the phase of the travelling waves this may be constructive or destructive, therefore amplifying or diminishing the wave at that point (Gartenhaus 1977). It should be noted that it can be hard to identify points where the interference could cause problems as waves travelling in opposite directions will pass through regions of constructive and destructive interference.

3. Methodology

The water distribution system investigated in this paper includes a network of trunk and supply mains and local distribution systems supplied by a single pumping station where the occurrence of transient was suspected. This area was monitored using high speed pressure data loggers. When the logging period started the source of transients was not known. Pressure traces were first recorded in a small domestic estate by the installed loggers. The recorded traces led to a more detailed investigation to identify the source. Further studies followed with a view to double check the result through cross verification from more than one area. This also allowed an investigation of the extent of the transient propagation. As a result of the data collection procedure the monitored locations will be reported as two separate case studies (comprising of measuring points on trunk, supply mains and distributions pipes), plus some additional monitoring locations on the trunk mains, see Figure 1.

The network configuration was constructed based on GIS data from the water utility company. It should be noted that some simplifications to the network representation were made. Although the major junctions are included in the analysis in this article, changes in pipe diameter and material were not captured accurately from the GIS data. In addition the GIS data includes only the trunk, supply and distribution pipes; there was no information on the small supply connections to customers. It should be noticed that, despite interviewing the utilities engineers, there is also a degree of uncertainty in the properties and the exact system configuration at the time of the pressure data measurement.

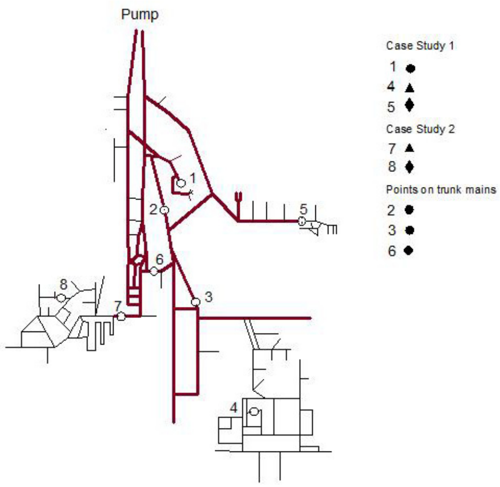

Figure 1. Network schematic (not to scale) with highlighted logging points,
▬ trunk and supply mains, — distribution pipes,
monitoring points from: ● trunk mains, ♦ DMAs supply mains and ▲ distribution pipes.

Case Study 1 presents the data from location 1 (trunk main), location 4 (in a distribution system, DMA) and location 5 (at the inlet to a DMA). These locations are where the transient waves were initially detected. From this the source was identified as the inlet pump station after investigation of pressure traces from the logging points and digital data from the supply pump.

Case Study 2 includes two monitored locations in a different section of the pumped system, location 7 on the supply main at the entrance to a district metered area and location 8 within the area.

Additional monitoring, was undertaken at locations 2, 3, 6 (on the trunk mains), as a third phase of study to support the analysis of differences between trunk mains, supply main and distribution pipes.

3.1. Sensors

The measured time domain pressure signals of transients were obtained using a set of custom built pressure transducers (Race Technology). The pressure traces were recorded continuously for 2-week periods in each location. All the recordings were digitized with 14 bit precision over a 20 bar range. A GPS receiver in the loggers allowed for synchronization between loggers. The loggers were installed to fittings on fire hydrants for the duration of the logging periods.

3.2. The shortest path algorithm

In order to explore the measured transient behavior it was desirable to find a way to calculate the shortest path for the wave to travel between the measurement points and from the source. Various graph theories have previously been used in topological clustering analysis of water distribution system (Perelman & Ostfeld 2011) and clustering of pipe breaks (Oliveira et al. 2011). They are also commonly recognized in routing and in GPS Technology to find the shortest path between a starting point and a destination. In the work presented the network connections were denoted as a simple non-directional graph, with connections weighted by length. Dijkstra's algorithm was used to find the shortest path (Dijkstra 1959) since it provided the most simplistic solution for the analysis.

4. Experimental results and analysis

4.1. Case Study 1

Figure 2 shows the pressure trace for two weeks of data collected from locations 1 (trunk main), 4 (distribution pipe) and 5 (pre-DMA supply main). The pressure recorded at location 1 has the greatest static pressure as it is nearer the pump (approximately 3.4 km). Locations 4 and 5 are 7.7 and 7 km respectively from the pump, however the static pressure at location 4 is slightly higher than that at location 5. This is likely to be due to the difference in elevation between the two points (loc 4 = 119 m, loc 5 = 114 m, above sea level), or the difference in energy lost to friction. It can be seen that the diurnal patterns at location 1 and 4 are similar however differ significantly from that recorded at location 5. It can be observed that there are well defined repeating transients, occurring regularly four times a day, visible in all three pressure traces.

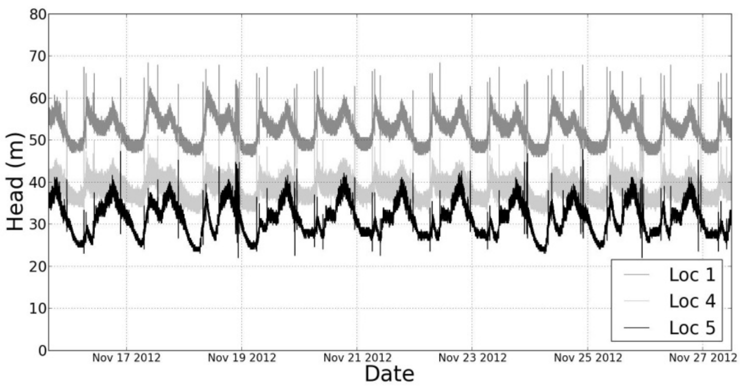

Figure 2. Two weeks of pressure data (down sampled to 1Hz for plotting purposes) from three different locations. Location 1 is within a distance of about 3.4 km from the pump and locations 4 and 5 are situated within and at the inlet to a small distribution network, 7.7 km and 7 km respectively.

The source of the transients was identified as the pump which feeds the entire region. The transients were found to align directly with the switching on and off of the pump which was recorded in available digital telemetry data, Figure 3.

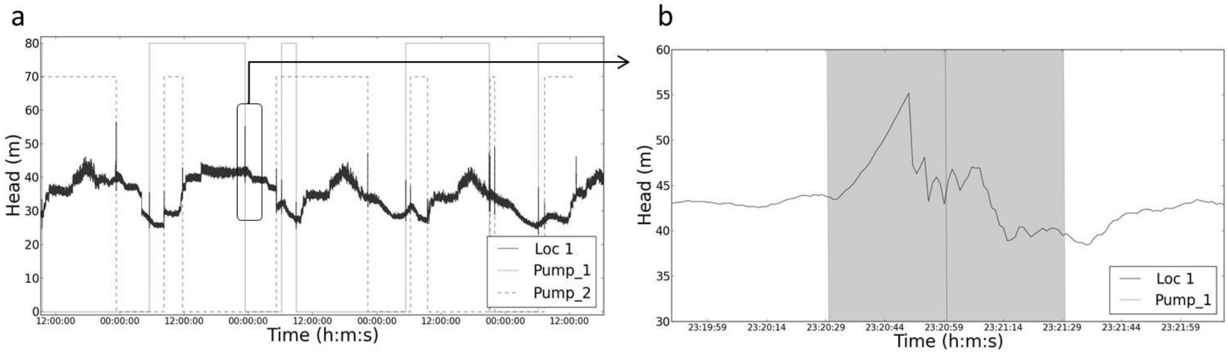

Figure 3. (a) Pressure trace from location 5 (down sampled for plotting purposes) and the pump switching on/off; (b) Magnification of one of the pressure transients with ±0.5 min accuracy of the digital event (shaded area). The vertical line represents a single pump operation.

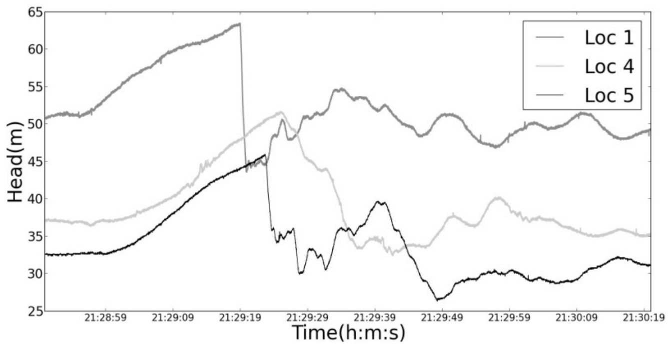

Figure 4. Close up of one of the transients just after 9 pm, at maximum frequency (100 Hz).

Figure 4 shows a time interval of 1.5 min where a transient trace is recorded at the three case study 1 locations. It can be seen from the plot that the wave arrives initially at location 1, closest to the pump, before reaching location 5, then 4. The transient wave is associated with a smooth increase in pressure, followed by a sharp decrease, seen at locations 1 and 5, on the trunk and supply mains. The wave shape at location 4 is modified and exhibits a shallower decrease in pressure. After the initial rise and fall in pressure there continues to be some oscillations of pressure before the system stabilizes. Figure 5 shows the same pressure traces aligned according to the occurrence of the peak pressure and with the initial mean pressure subtracted to allow a comparison of the shapes and magnitudes of the pressure waves. From this figure it can be seen that the magnitude of the wave is not diminished from location 1 to 4 to 5, in fact there is a slight increase of peak wave pressure at location 4 in the distribution system.

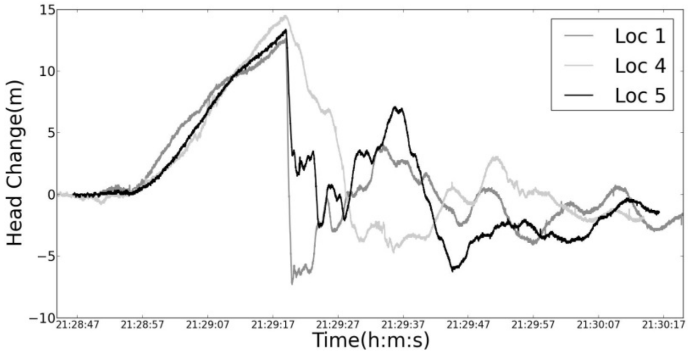

Figure 5. Three pressure traces from the locations 1, 4, 5 aligned according to occurrence of peak and normalised by subtracting initial mean pressure at each location.

The magnitudes of the initial upsurge of the transients were calculated by subtracting the mean pressure before the transient wave from the peak pressure. The upsurge amplitudes for the three Case Study 1 points are given in Table 1.

Table 1. Calculated amplitude values for Loc1, 4, 5 (Case Study 1)

Location	Pre-transient mean (m)	Upsurge amplitude (m)
Loc1	50.8	12.7
Loc4	38.1	13.6
Loc5	32.7	13.2

4.2. Case Study 2

Figure 6 presents the pressure traces recorded at locations 7 (supply main) and 8 (distribution pipe) which are 5.8 and 6.8 km away from the pump respectively. This area was chosen to enhance the findings from Case Study 1. The two monitoring points are located around a small domestic estate where most pipe diameters were found to be in the range 4” to 6” in diameter with a predominantly looped layout.

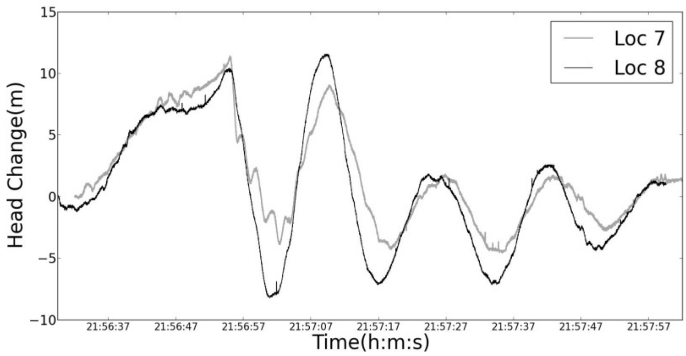

Figure 6. Pressure traces from locations 7 and 8 (small looped domestic estate) aligned according to occurrence of peak and normalised by subtracting initial mean pressure at each location.

The traces in Figure 6 have been aligned by the initial peaks. It was found that the wave arrives at location 7 2.5 s before location 8. The mean pressure at location 7 was about 10 m lower than at location 8, accounted for by the difference in elevation between the two points; location 7 being 118 m, location 8 being 108 m above sea level. It can be seen that the initial pressure rise is very similar in the two traces; a slow rise followed by a slight increase to a peak followed by a sharp decrease. Location 7 outside the distribution system exhibits some additional low amplitude, high frequency oscillations not seen in the distribution system. Of major interest is the fact that the amplitude of the second peak at location 8 is higher than that of the first peak. The amplitude of the second wave upsurge was 12.2 m pressure head compared to the 11.1 m of the first one. This shows that rather than diminishing as the waves travels into a distribution system there are mechanisms that allow the peak pressure to increase, over time as well as over distance.

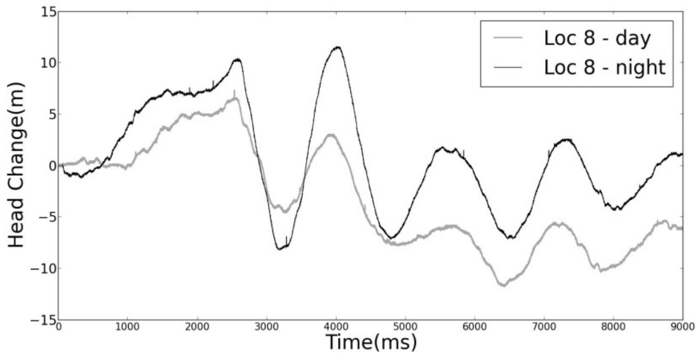

Figure 7. Typical transients from location 8 during night (black line) and day time (gray line)

It was found that the pressure trace seen in Figure 6 was not characteristic for all times of day. Figure 7 shows typically pressure traces recorded during the day and at night from location 8. It can be observed that the transient wave that occurs during the day time is damped/ dissipated rapidly, but that at the same location at night appears to experience some constructive interference, or other effect.

4.3. Additional monitoring

Locations 2, 3 and 6 were on the trunk mains (see Figure 1) as an additional source of transient data. Figure 8 shows these pressure traces aligned according to the occurrence of the peak pressure and with initial pre-transient mean pressure subtracted. From this figure it can be seen that the magnitude of the initial pressure rise at all three locations is almost the same despite varying distances from the pump: 4.8 km, 6.2 km and 3.8 km for locations 2, 3, 6 respectively. The smooth increase in pressure is followed by a sharp decrease seen in all three of the traces, however, wave shape at location 3 shows a slightly shallow fall in pressure. After the initial rise and decrease in pressure there continues to be some oscillations of pressure before the system stabilizes which was seen in all three pressure traces.

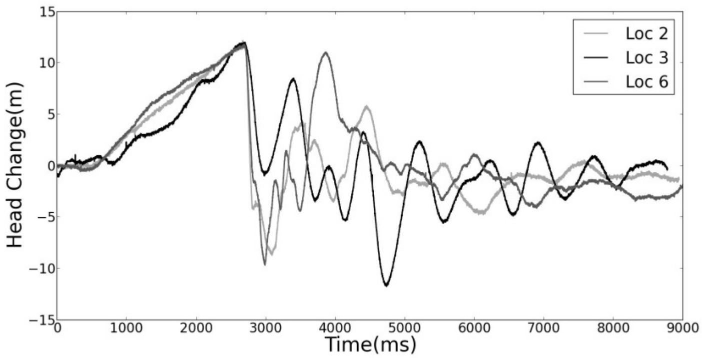

Figure 8. Pressure traces from the locations 2, 3, 6 aligned according to occurrence of peak and normalized by subtracting initial mean pressure at each location.

4.4. Damping / Dissipation Effects

To assess the wave damping and dissipation effects the results from case studies 1 and 2 were related with results from the additional monitoring locations. Outcomes were combined and analyzed looking at changes in the transient upsurge amplitude with respect to the shortest travel distance and increasing number of junctions. The results are presented in Figure 9.

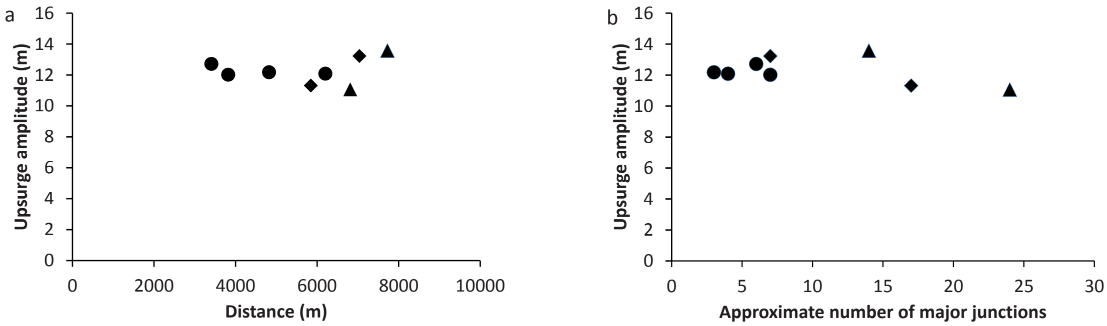

Figure 9. Changing of the transient amplitude with respect to (a) distance (m) and (b) approximate number of major junctions (● monitoring points from the trunk mains, ♦ supply mains and ▲ distribution pipes).

Figure 9 (a) suggests no relationship between distance and upsurge amplitudes. The change in upsurge amplitude is very small compared to the uncertainty of the network. There is no clear decrease with distance as might commonly be expected. From this analysis it can be seen that the peak transient pressure does not change or decrease with distance. This may have been expected as a consequence of sudden reductions in pipe diameter, which would tend to become more numerous over increasing distances. However it can be observed (Figure 9 (b)) that as the approximate number of major junctions increases there is also no obvious change in the upsurges amplitude.

5. Discussion

Although transient activities, due to fact such as pump operations, may be expected through trunk mains as a result of direct transmission from source, in the distribution systems the commonly held assumption is that these are expected to dissipate due to the network complexity. The results presented here, however, show that propagation through the network does not always result in damping or dissipation of transients, with measured transient pressures persisting throughout the studied network.

Case Study 1 (Figure 5 and Figure 9) shows no decrease in transient upsurges amplitude despite progression from trunk to distribution pipes. It has been shown that pipe contractions can result in increases in transient wave magnitude (Ellis 2008). The network examined here is typical in that it has larger trunk mains (diameters 450 mm to 600 mm) feeding smaller distribution pipes (diameter 100mm to 200 mm) (Ratnayaka et al. 2009). It is possible to claim that this configuration may therefore explain this observation. In addition the presence of dead ends in the immediate vicinity could have contributed to constructive interference and transients arriving via different pathways for the locations.

In Figure 5 the pressure trace at location 4 does not decay in the same way as at location 1 and 5 respectively; a shallower decrease in pressure can be observed, forming a triangular wave as opposed to a saw tooth shape. This could possibly be due to the increase in number of junctions and dead ends typical for a local distribution network. As was previously noticed (Swaffield & Boldy 1993), large numbers of junctions, particularly with dead ends, can cause the pressure in the initial wave to be trapped in these sections before slowly being returned back to the main pipeline. This tends to have the effect of elongating the wave and changing the wave phase (Edwards & Collins 2013). This may account for the change in the shape of the wave in Case Study 1, and also the increase in the wave magnitude as shown in Case Study 2. However the exact response of the system will be highly dependent on the exact network geometry which may explain why these two effects appear to be very different.

The results presented in Case Study 2 identified variations in pressure transients during the course of a day, Figure 7. Following the investigation of the digital pump data it was found that the variable speed pump is constantly running and is assisted firstly by a single fixed speed pump, secondly by another fixed speed pump, and finally by an additional variable speed pump. The specific transient that resulted in the higher second peak at location 8 were related to when the second fixed speed pump was off and the first fixed speed pump switches off. Although the exact mechanism that causes the particular pressure change is not known, it is likely to be one of two factors. It could be due to some function of the flow velocity in the network or some superposition of two waves that have been attenuated differently as they pass through the network. It can then be concluded that transient behavior is not only a result of the network but also of source and how it is generated.

6. Conclusions

High resolution pressure data obtained from different points in a complex water distribution network were analysed. The measured data widens the insight into the behaviour of transient waves in operational distribution networks. It was found that:

- Pressure transients can propagate throughout water distribution systems (and remain clearly distinguishable from background features), going against the generally held belief that the complexity of the systems damps and dissipates the transients,
- In some cases network configuration may lead to transient amplification,
- Transient behavior is not only a function of the network but also the source and how it is generated

Thus this work illustrates the complexity of transient behavior in real distribution networks and highlights some of the areas where we need to improve our understanding and tools to capture such behavior and hence predict and manage impacts.

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